

# **Remote Sensing in Fluctuating Range-Dependent Littoral Environments with Clutter**

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Grant Number: N000140510114

## **LONG-TERM GOALS AND OBJECTIVES**

The ongoing research addresses two areas crucial to the effective performance of Navy sonar systems in range-dependent shallow water environments. The first is an understanding of the characteristics of clutter and background reverberation in long range sonars. This is being used to develop operational and signal processing techniques to mitigate the effects of clutter and reverberation in order to enhance detection of man-made targets. In the second area, the dominant causes of fluctuation in measured acoustic signals is examined and used to determine the extent to which environmental variabilities limit our ability to perform source localization and environmental parameter estimation through match-field processing and beamforming in fluctuating ocean waveguides.

## **APPROACH**

The research effort involves analyzing the vast amounts of data collected during the 2001 and 2003 experiments of the Geoclutter Program[1] off the New Jersey Coast. Theoretical models for multi-static scattering and reverberation in range dependent environments have also been developed and are being validated to aid in the understanding of the causes and characteristics of clutter and reverberation.

## **WORK COMPLETED AND RESULTS**

- **Inferring fish population and behaviour from long range sonar**

Using data from the Geoclutter Acoustic Experiment (GAE) of 2003 on the New Jersey Continental shelf, it was previously determined using statistical analysis that prominent clutter measured by long range sonar operating in continental shelf environments with little bathymetric relief is predominantly caused by fish.[1,2] This was confirmed by temporally and spatially correlating wide area data in the low- to mid-frequencies from the long range sonar with high-frequency data from a down-directed fish finding sonar. Scattering from fish schools and shoals can camouflage or be confused with the returns from an intended target, like an undersea vehicle. This makes it important to understand the dynamic characteristics of acoustic returns from fish for clutter mitigation. The experiment also demonstrated that it is possible to image and study large scale fish population and behaviour instantaneously over wide areas spanning thousands of square kilometers using long range sonar making it an important tool in fisheries research.

Data from GAE 2003 have now been inverted to estimate the population and areal densities of fish that lead to clutter in long range sonar using a bistatic, range-dependent scattering and reverberation model based on the parabolic equation (PE). The wide area acoustic images of the ocean environment in the 390-440 Hz frequency range have been corrected for source level, 2 way transmission loss, and the

Report Documentation Page				Form Approved OMB No. 0704-0188	
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1. REPORT DATE <b>30 SEP 2005</b>		2. REPORT TYPE		3. DATES COVERED <b>00-00-2005 to 00-00-2005</b>	
4. TITLE AND SUBTITLE <b>Remote Sensing in Fluctuating Range-Dependent Littoral Environments with Clutter</b>				5a. CONTRACT NUMBER	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S)				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) <b>Northeastern University, 409 Dana Research Center, Boston, MA, 02115</b>				8. PERFORMING ORGANIZATION REPORT NUMBER	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSOR/MONITOR'S ACRONYM(S)	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S)	
12. DISTRIBUTION/AVAILABILITY STATEMENT <b>Approved for public release; distribution unlimited</b>					
13. SUPPLEMENTARY NOTES <b>code 1 only</b>					
14. ABSTRACT <b>The ongoing research addresses two areas crucial to the effective performance of Navy sonar systems in range-dependent shallow water environments. The first is an understanding of the characteristics of clutter and background reverberation in long range sonars. This is being used to develop operational and signal processing techniques to mitigate the effects of clutter and reverberation in order to enhance detection of man-man targets. In the second area, the dominant causes of fluctuation in measured acoustic signals is examined and used to determine the extent to which environmental variabilities limit our ability to perform source localization and environmental parameter estimation through match-field processing and beamforming in fluctuating ocean waveguides.</b>					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT <b>Same as Report (SAR)</b>	18. NUMBER OF PAGES <b>7</b>	19a. NAME OF RESPONSIBLE PERSON
a. REPORT <b>unclassified</b>	b. ABSTRACT <b>unclassified</b>	c. THIS PAGE <b>unclassified</b>			

azimuth-dependent beam pattern of the receiving array to yield estimates of the scattering strength per unit area of the ocean environment. This data was compared to estimates of fish density along the tracks of the fish finding sonar to determine the average target strength of each fish in the 390-440 Hz range and it was found to be around -50 dB re 1m. This target strength estimate was then applied to the wide area scattering strength images of the ocean environment to obtain images of the areal fish population densities.[3,4] Video images of wide area fish population were generated at 50s update rate over the course of daylight hours for several days in May 2003. These images show that fish shoals are highly dynamic in time and space.

On May 14 of the 2003 Experiment at site 2, we observed a massive shoal of fish extending over 12 km width with densities in some regions exceeding 1 fish/m<sup>2</sup>. These shoals appear to line up with an outward edge along the 80m to 100m bathymetric contour close to the New Jersey continental shelf edge. The shoals then underwent a dynamic morphological transformation during the course of the day before dispersing and splitting up into smaller shoals towards the end of the day. This same pattern of behaviour was also observed the next morning at the same site, showing that fish behaviour is very much connected to oceanographic processes and geography. [3,4]

The total population of fish contained in the survey box spanning an area of 15 km by 15 km on May 14 was on the order of 24 million fish. Shoaling regions with fish densities larger than 0.2 fish/m<sup>2</sup> account for roughly 2/3 to 1/2 of the total population and can undergo drastic fluctuation in fish population with dispersal rates on the order of 0.5 million fish/minute. Immediately outside the shoal are a diffuse population of fish with densities of less than 0.2 fish/m<sup>2</sup>. They form a more stable population over time that accounts for roughly 1/3 to 1/2 of the total population of fish. The fluctuations in fish population in the shoal are primarily due to convergences and divergences in areal densities above and below the 0.01 fish/m<sup>2</sup> threshold (refer to next section) where seafloor scattering mechanisms become important and mask the returns from fish. They may also be due to fish entering and leaving the survey area. [3,4]

We are presently analyzing the horizontal structure of the massive fish shoals using image processing techniques to determine the characteristics of the various schools contained within the shoals, including their coherence areas, connectivity, translational motion and speeds. This will provide us with clues and insights to large scale fish behaviour and their modes of communication and motion. We are also investigating long range sonar data at higher frequencies, in the 800 Hz to 1.5 kHz range and contrasting them to data collected at lower frequencies to determine if there is sufficient information to note changes in the scattering characteristics of the fish shoals that allow for possible species differentiation and identification.

- **Minimum fish population density necessary for imaging**

In order to determine the limits of the long range sonar for imaging fish, we investigated the minimum fish densities necessary to stand above the background reverberation. [5] Images of the mean and standard deviation were calculated from scattering strength images of the ocean environment formed from the long range sonar data over tracks of the receiver ship over the course of the day. Areas with low mean and low standard deviation in scattering strength were identified as regions devoid of prominent scatterers as shown in Fig. 1. A time history of the scattering strength levels in pixels with low mean and standard deviation throughout the area were compared to other pixels drawn from the area. The time history plot in Fig. 2 clearly shows the scattering strength levels in regions with fairly stable fish activity, regions with passing fish schools and regions that comprise primarily of background reverberation. The background scattering strength levels are on the order of -67 dB/m<sup>2</sup> re

1m which correspond to fish densities on the order of  $0.01 \text{ fish/m}^2$ . This is then the minimum density necessary to image fish. It is noteworthy that in regions and times with prominent fish activity or passing schools, the scattering strength levels stand up to 3 to 4 orders of magnitude above the background reverberation.

- **Range-dependent scattering and reverberation models: Calibration with real data**

Several unified scattering and reverberation models were developed in support of the ONR Acoustic Clutter Program.[6-10] They include a range-dependent model based on the parabolic equation (PE) that can be used to efficiently model scattering from a random spatial distribution of random targets that obey the sonar equation in the waveguide and a similar but range-independent waveguide model based on normal modes for scattering from extended objects. Both these models are bistatic and fully 3D, and the latter model also accounts for modal coupling between propagation and scattering caused by extended objects in the waveguide. These models have been applied to examine both coherent and diffuse scattering measured after beamforming and match-filtering on an array of sensors from schools of fish, plankton, volume inhomogeneities in the sea bottom, roughness on the seafloor, extended seafloor and sub-bottom features such as river channels and reflective strata, and internal and surface waves. Preliminary analysis with these models have shown that scattering from large and densely populated schools of fish can stand significantly above the background reverberation to cause clutter.[10] The models have also been used to demonstrate that scattering from sub-bottom features such as buried river channels and subsurface reflectors is negligible compared to bottom reverberation.[6-9] The effect of upslope and downslope bathymetry on respectively raising and reducing the bottom reverberation have been quantified.[6-8]

The range-dependent PE-based model for fish scattering has already been calibrated and applied to the GAE 2003 data to obtain estimates of fish population and density. We are now presently calibrating both the PE and normal-mode reverberation models with background scattering strength data from GAE 2003 and 2001 to determine the characteristics and dominant source for background reverberation. The likely mechanisms include seafloor roughness or volume anomaly scattering, low density schools of fish, as well as internal waves and bubble clouds. [5]

These calibrated models for background reverberation, fish and target scattering will be applied in future experiments planned for 2006 at Gulf of Maine to aid in experimental design, including the placement of sensors for optimal fish detection and imaging under the NOPP program. The Gulf of Maine is a more challenging environment to model with both upslope and downslope bathymetry on Georges bank that can be taken advantage of for enhanced fish imaging.

- **Statistical moments of forward field in a random ocean waveguide**

The mean, mutual intensity and spatial covariance of the acoustic field forward propagated through a random ocean waveguide has been derived analytically using Green's theorem and fundamental statistical theory. [11] The model can be applied to both discrete and continuously varying random surface and volume inhomogeneities, arbitrarily large compared to the acoustic wavelength and of arbitrary acoustic impedance, density and sound speed contrast compared to the surrounding medium. This approach differs substantially from restrictive perturbation theory and Rayleigh-Born approximation methods where parameters such as surface slope and changes in medium properties must be small. The model takes into account the full 3-dimensional (3D) multiple scattering interaction of the medium inhomogeneities with the acoustic field. The model is advantageous because it can handle both range and cross-range dependent variation in the scattering properties of the medium

inhomogeneities. In particular the model can handle both correlated (extended) and uncorrelated (small) scatterers in cross-range within the Fresnel width and in depth from source to receiver.

The mean forward field after multiple scattering in the random ocean waveguide is expressed in terms of the incident field except for a complex change in the horizontal wavenumber for each mode. This change describes attenuation and dispersion induced by medium's inhomogeneities, including potential model coupling along the propagation path. By invoking the generalized waveguide extinction theorem, we show that the attenuation from forward scattering for each mode can be expressed in terms of the expected waveguide modal extinction density of the medium. This provides a convenient method for estimating power losses after multiple forward scattering. The covariance of the forward field between two receivers in a random waveguide can be expressed as a modal sum of covariance terms that depend on the modal extinction density as well as the covariance of the medium's scatter function density which couples each mode to all the other modes.

The formulation has been applied to study the effect of forward acoustic propagation through random internal waves in continental shelf environments.[12] Simulations with the model indicate that the forward field moments are highly dependent on the correlation length scale of the internal wave field and their displacement height standard deviation. It is also shown that the 3D scattering effects can become important when the Fresnel width exceeds the cross-range coherent scale of the medium's inhomogeneities. The model is also being applied to investigate the effect of scattering by bubble-clouds, schools of fish, sea surface, seafloor and seabed anomalies on acoustic wave propagation.

- **Effect of environmental fluctuation on range and bearing estimation in a random ocean waveguide**

The analytic model developed for wave propagation in a random waveguide is being applied to examine the effect of waveguide fluctuation in estimating the range and depth to a radiating target by various methods including passive match-field processing using a vertical line array. [13] Preliminary analysis indicates that in a slightly random waveguide, when the coherent field dominates across the array, it may be possible to estimate the range to a target by passive match field processing (MFP) if the amount of dispersion caused by random scattering in the waveguide is known. If this dispersion is unknown, there may be a bias in the range estimation using MFP that can be significant. When the incoherent field dominates in a highly random waveguide, range estimation by MFP becomes extremely challenging. The modal interference structure that is required for the inversion by MFP is no longer present in the waveguide when the incoherent field dominates, as the waveguide modes become completely randomized by scattering with random inhomogeneities. Statistical analysis shows the sample sizes necessary for source localization in range and depth are at least an order of magnitude larger in the highly random waveguide dominated by the incoherent intensity as compared to the slightly random waveguide dominated by the coherent intensity.

The formulation is also being used to examine the effect of waveguide fluctuation on estimating the bearing to targets by beamforming the received field on a horizontal array of sensors. The analytic model for the mean and covariance of the forward field between two receivers after forward propagation in a random waveguide will be passed through a beamformer to analytically determine the mean beamformed field and expected beamformed intensity in the random ocean waveguide. Preliminary analysis indicates that when the received field from a target is dominated by the coherent intensity, the mean beamformed field can lead to a bias in bearing estimation due to dispersion in the random waveguide. Dispersion causes a change in the phase speed of modal plane wave arrivals on the array and can lead to errors in bearing estimation if not accounted for. This bearing estimation error

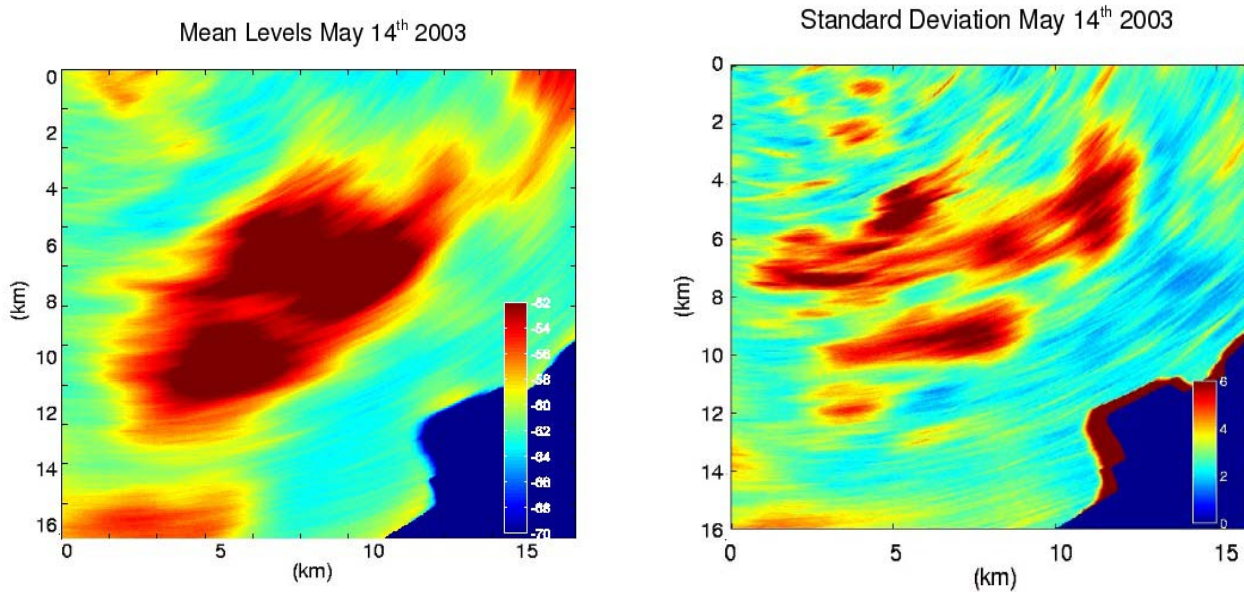
can be significant at endfire but disappears for broadside arrivals. When the incoherent intensity dominates for the received field from a target in the random waveguide, the expected beamformed intensity however, leads, to insignificant errors in bearing estimation.

- **Optimal array angular resolution in a random waveguide**

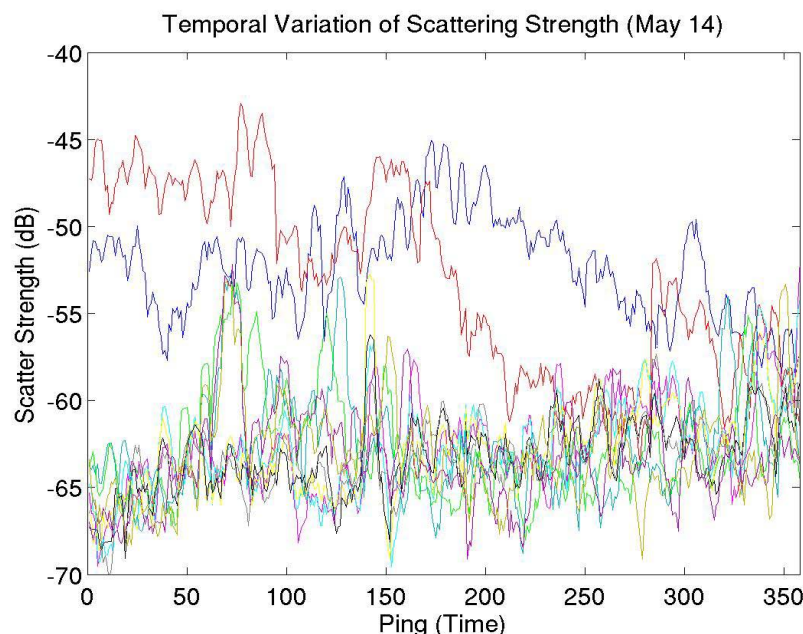
The angular resolution of an array after beamforming is inversely related to the length of the array. In order to improve on the bearing estimation to a target, it is necessary to increase the length of an array. However, it is known that the length of an array cannot be increased incessantly since the signals received on two sensors on the array becomes less correlated when the two sensors are spaced increasingly apart in a random waveguide. There exists a maximum length for the array beyond which no further gains in angular resolution can be obtained due to the loss of coherence of the array. The model developed here will be used to examine this expected maximum array length for optimal angular resolution in a random waveguide. The model will also be applied to determine the dominant scatterers in the random waveguide responsible for randomizing the field in cross-range that leads to a decorrelation in the received field across the array and a degradation in the array gain. The candidate scatterers to be investigated include schools of fish, internal waves, bubbles, surface waves, seafloor and bottom anomalies.

## IMPACT/APPLICATIONS

We have demonstrated the capability of the long range sonar as an extremely useful tool in fisheries research for rapidly imaging and quantifying fish populations over wide areas spanning thousands of square kilometers.



**Figure 1: Mean and standard deviation of scattering strength from the environment on May 14 2003 of the Geoclutter Acoustic Experiment at the New Jersey Strataform site measured by a long range sonar.**



**Figure 2: Temporal variation of the scattering strength for various pixels drawn from Fig. 1. The stable and fluctuating high levels are due to stable or passing fish populations. The stable low levels of around -67 dB correspond to background reverberation that could be due to diffuse scattering from the bottom or very low densities of fish.**

## RELATED PROJECTS

Research on several of the areas listed above are being conducted in collaboration with Nick Makris and his team at MIT. The results of this research also supports the National Oceanographic and Partnership Program (NOPP) on fish sensing and imaging.

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